The Performance of the First Optical Refrigerator

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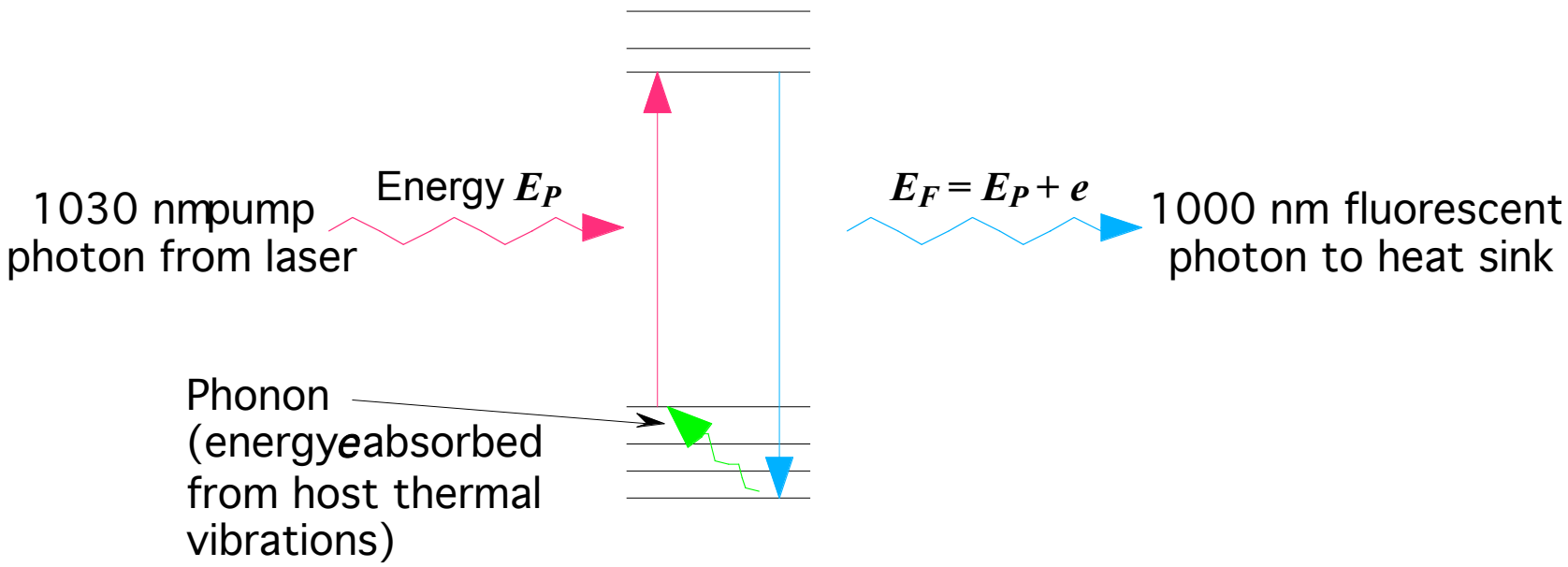
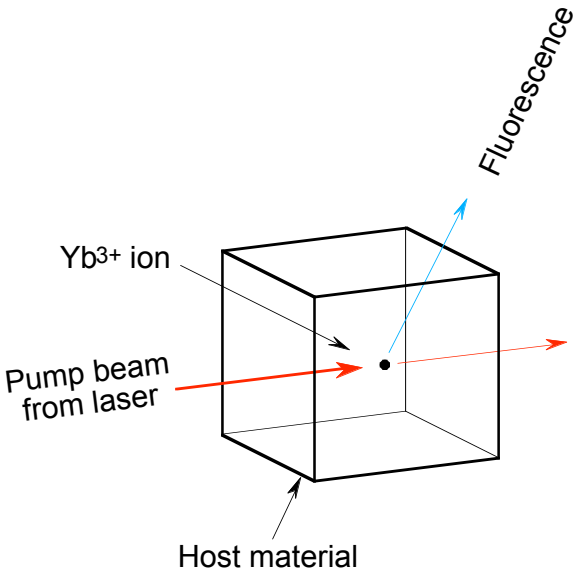
The Photon-Phonon Refrigeration Cycle



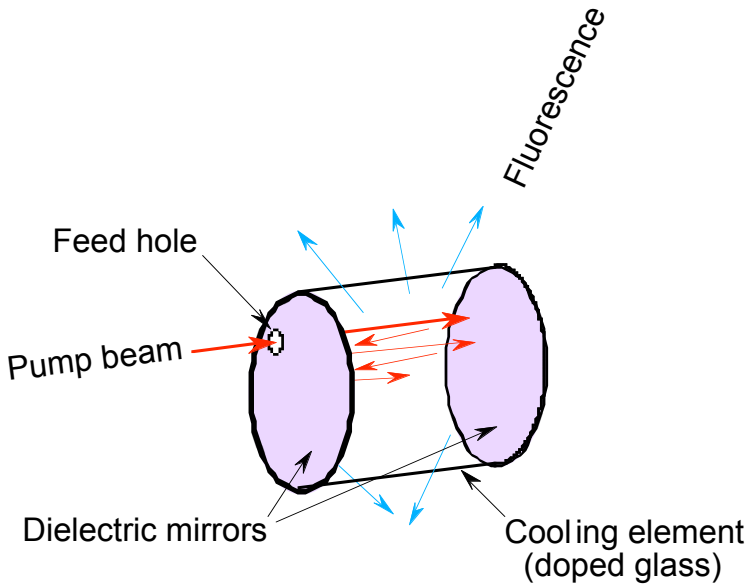
Energy levels of Yb^{3+} ion in ZBLAN glass host

Optical Cooling Process:
Optical Pump Photons Remove Heat Phonons

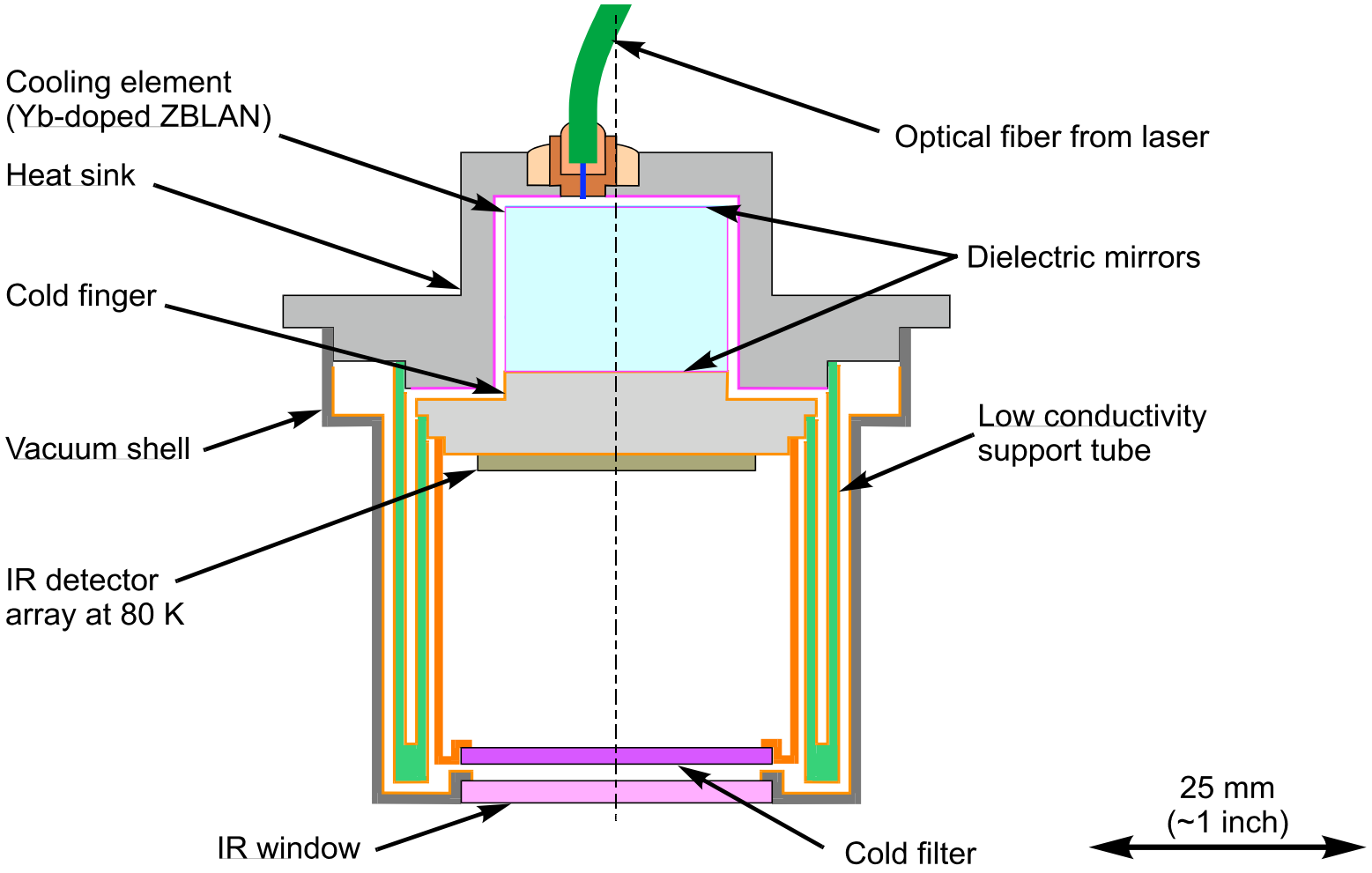


- **Pump photon absorbed by Yb dopant atom**
- **Photon re-emitted slightly bluer (higher energy)**
- **Energy difference comes from thermal vibrations (phonons) of host material**

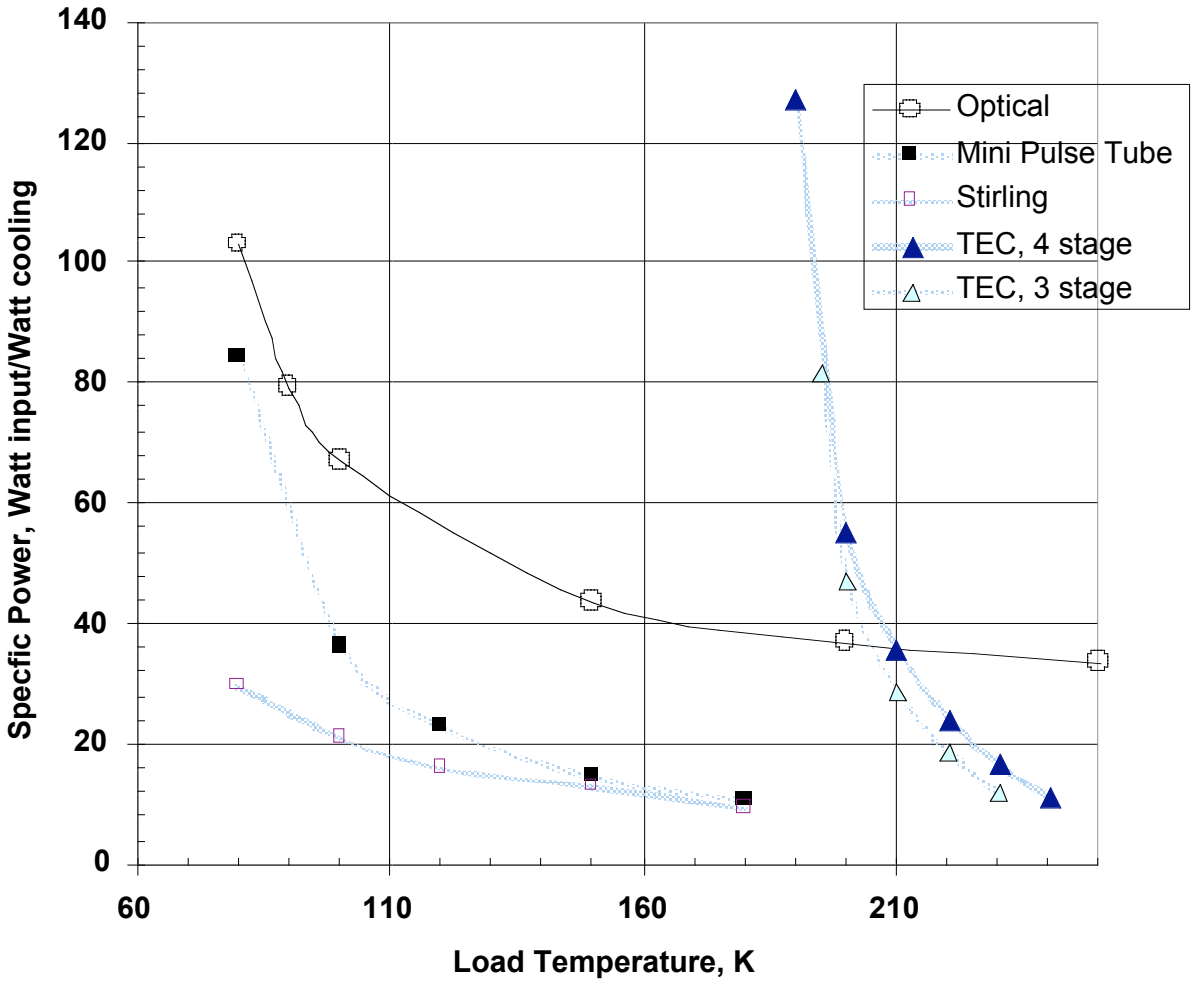
- **High-reflectivity mirrors provide long path length for pump beam**
- **Fluorescence escapes from uncoated sides of cooling element**



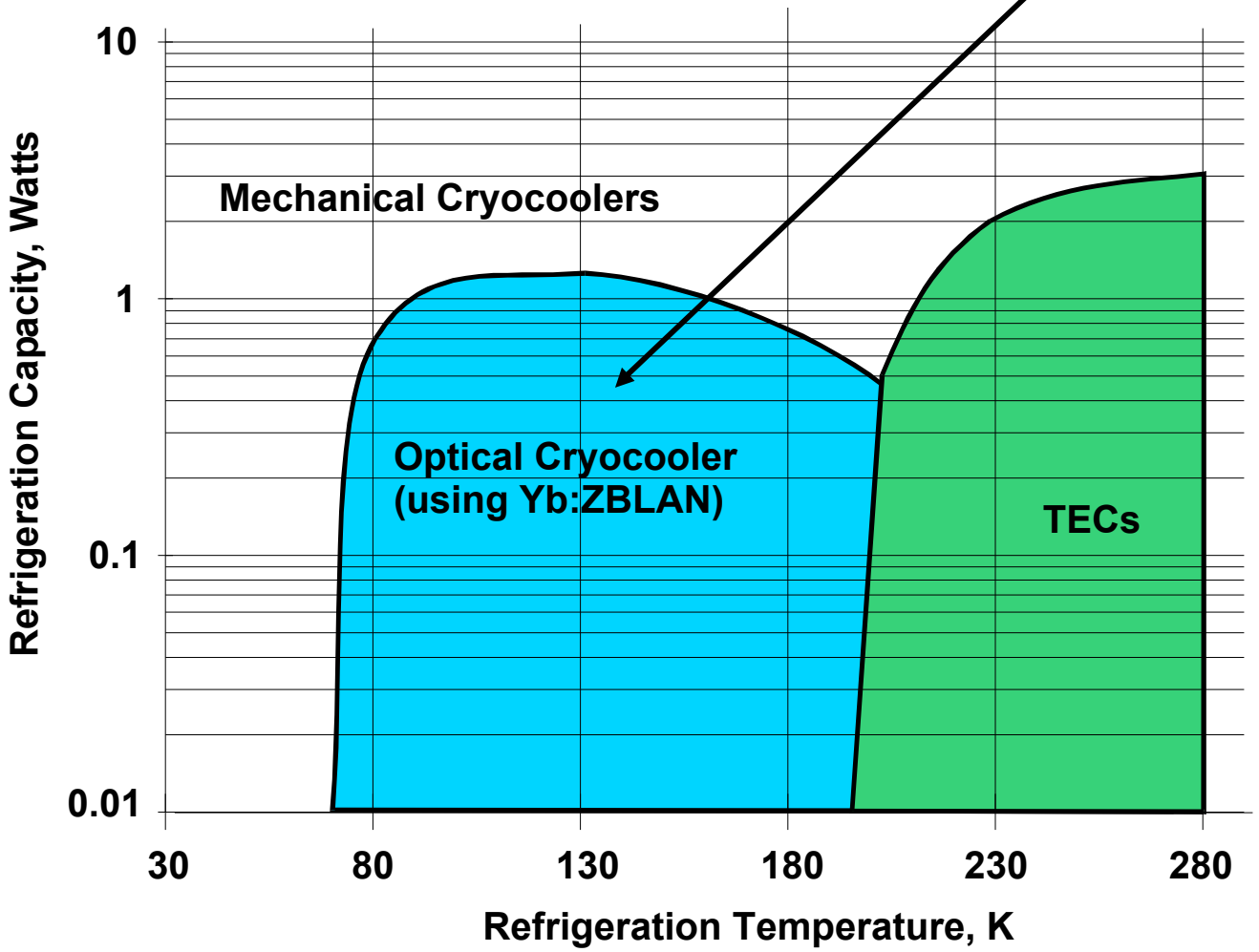
Compact IR Detector / Cryocooler Package Capable of Lifting 400 mW at 80 Kelvin



Calculated Efficiency of Optical Refrigeration is within an Acceptable Range



Optical Cryocooling has the Lowest Spacecraft System Mass in this Region



Comparison to other Cryocooler Technologies is Favorable in Many Areas

- **Vibration**
  - Optical cryocooler is solid state; zero vibration is an obvious advantage
- **Electromagnetic and magnetic noise**
  - Optical cold head uses only photons, no electrons: no noise
  - Laser can be remotely located to minimize noise; split Stirling machines can have remotely located compressors, but with significant drawbacks
- **Reliability and lifetime**
  - No moving parts, laser is the life limiting component
  - Solid state lasers are made up of many diodes whose output is joined together by optical "Y" junctions
  - Laser diode modules have lifetimes of several years with a Gaussian lifetime distribution
  - Redundancy is inherent; more can be added with no impact on thermal performance

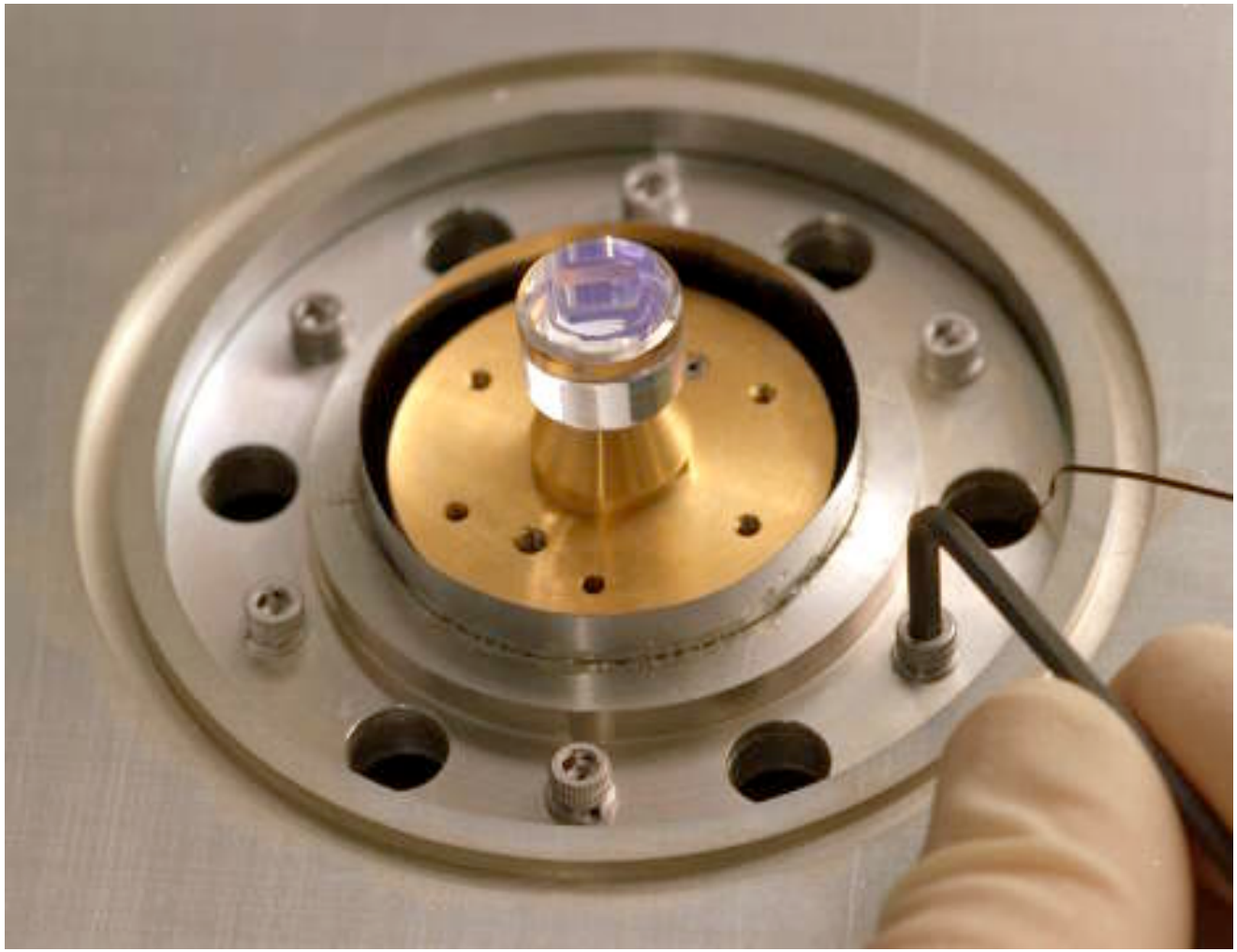
Comparison to other Cryocooler Technologies is Favorable in Many Areas (continued)

- **Extreme environments**
  - The glass cooling element is separated from the heat sink by a gap; it is inherently protected from physical stress
  - Glass cooling element has a compact form factor that withstand high accelerations
  - High temperature environment: fluorescent cooling process is not directly affected by temperature of the heat sink.

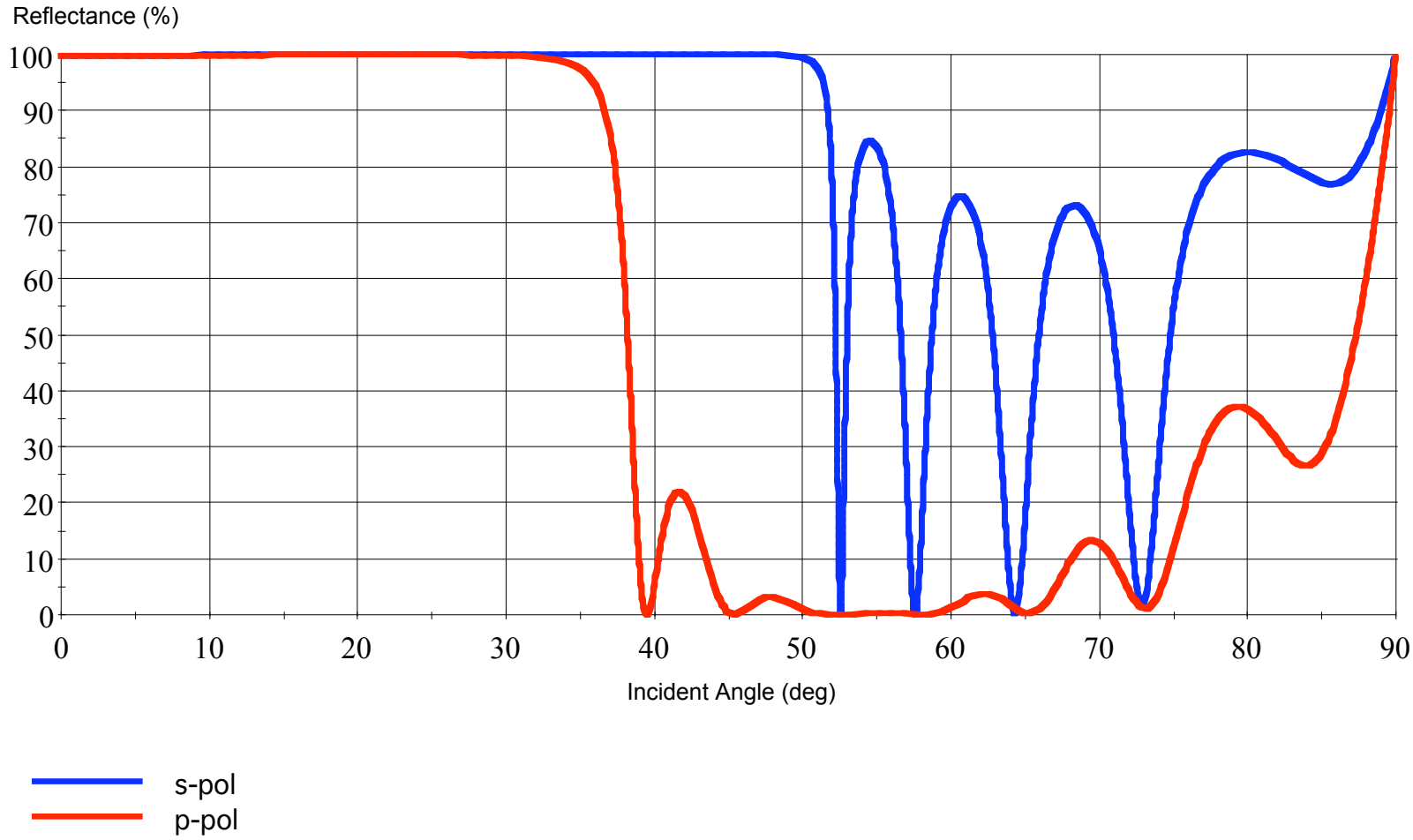
- **Miniaturization**
  - Complete cryocooler with less than 1 cm^3 volume appears possible.
  - Sub-millimeter diode lasers already exist

- **Cost**
  - Technology used permits low-cost manufacture
  - No high-precision mechanical assemblies
  - Material and process issues are all ones that have been worked out for high-volume industries

Early Refrigerator Design Depended on Dielectric Mirror to Shield Load From Fluorescence



Mirror Reflectance of 1/4 Wave Stack with Incident Light from Yb:ZBLAN Side Shows Leakage > 30°



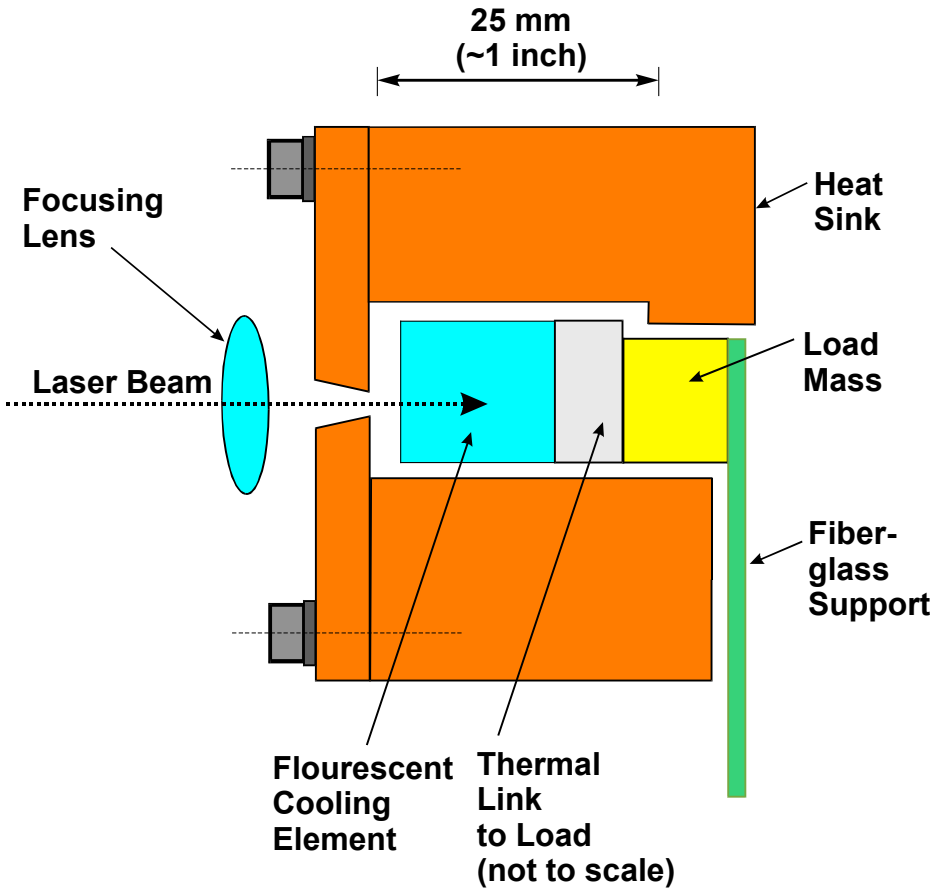
Effect of Mirror Leakage on Optical Refrigerator Performance

- As much as 27% of the light emitted by the cooling element leaks through a typical mirror stack and might be incident on the cooling load.

- Available heat lift ranges from optical cooling process ranges from 1 to 6% of the fluorescence, depending on temperature.

- The energy from the leakage has the potential to significantly reduce or even completely negate the cooling effect.

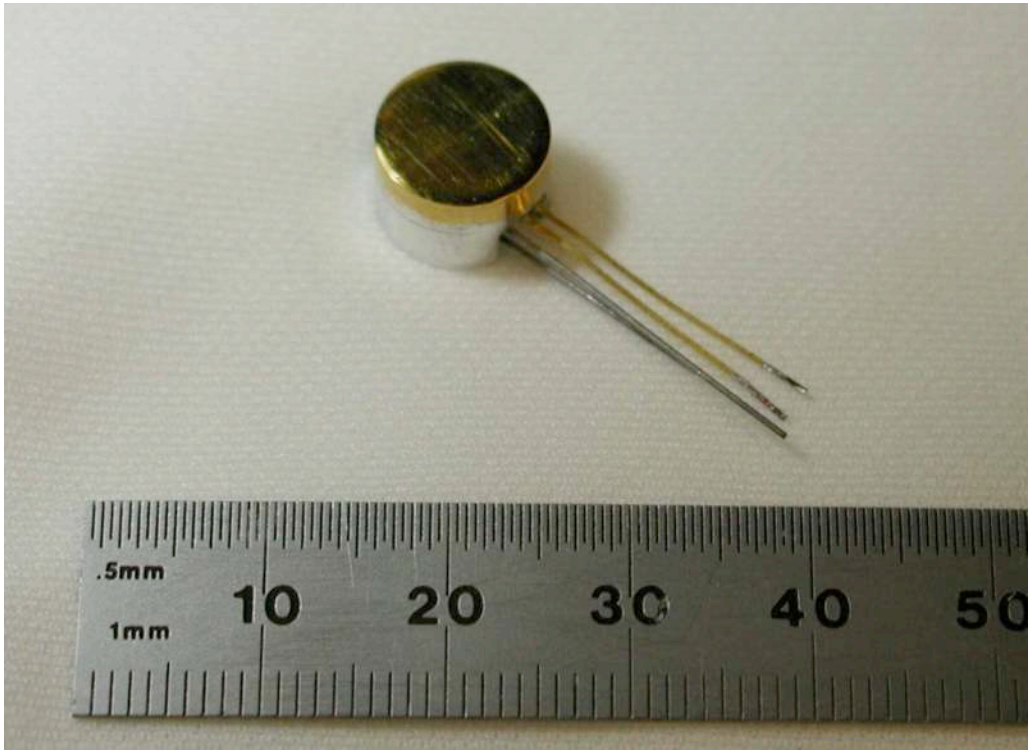
Test Refrigerator Design



- Is contained within a small vacuum chamber with a window for free space pump beam
- Has a copper heat sink surrounding the cooling assembly
- Cooling assembly
  - 2% Yb:ZBLAN fluorescent cooling element
  - Aluminum load mass with thermometer and heater
  - Proprietary element that provides the thermal link between fluorescent element and load mass

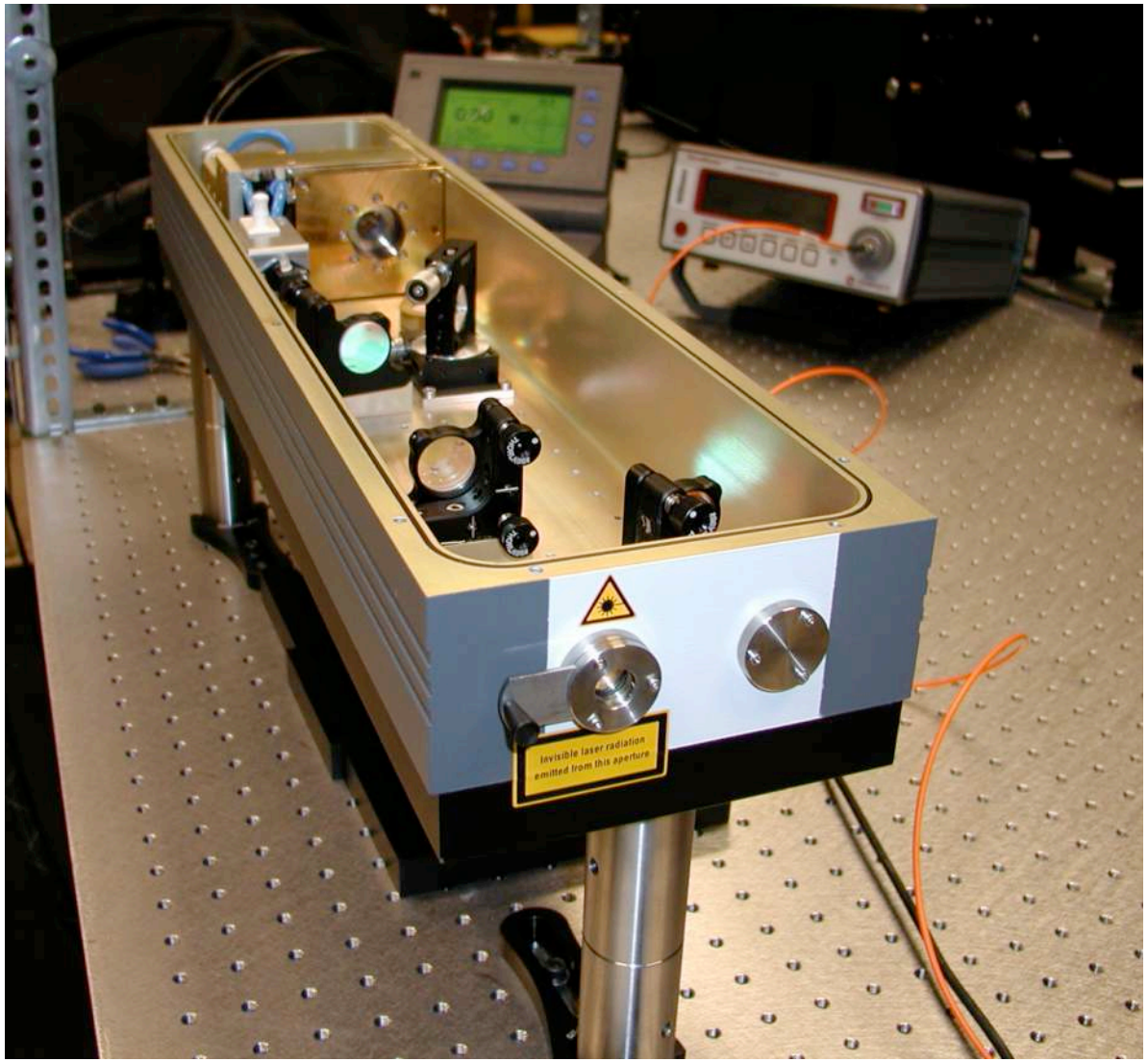
Load Mass Simulates IR Detector or Other Small Device to be Cooled

- 10 mm diameter by 6 mm long aluminum cylinder
- Weighs 1.1 grams
- Has a silicon diode thermometer and heater resistor bonded in a slot in the cylinder



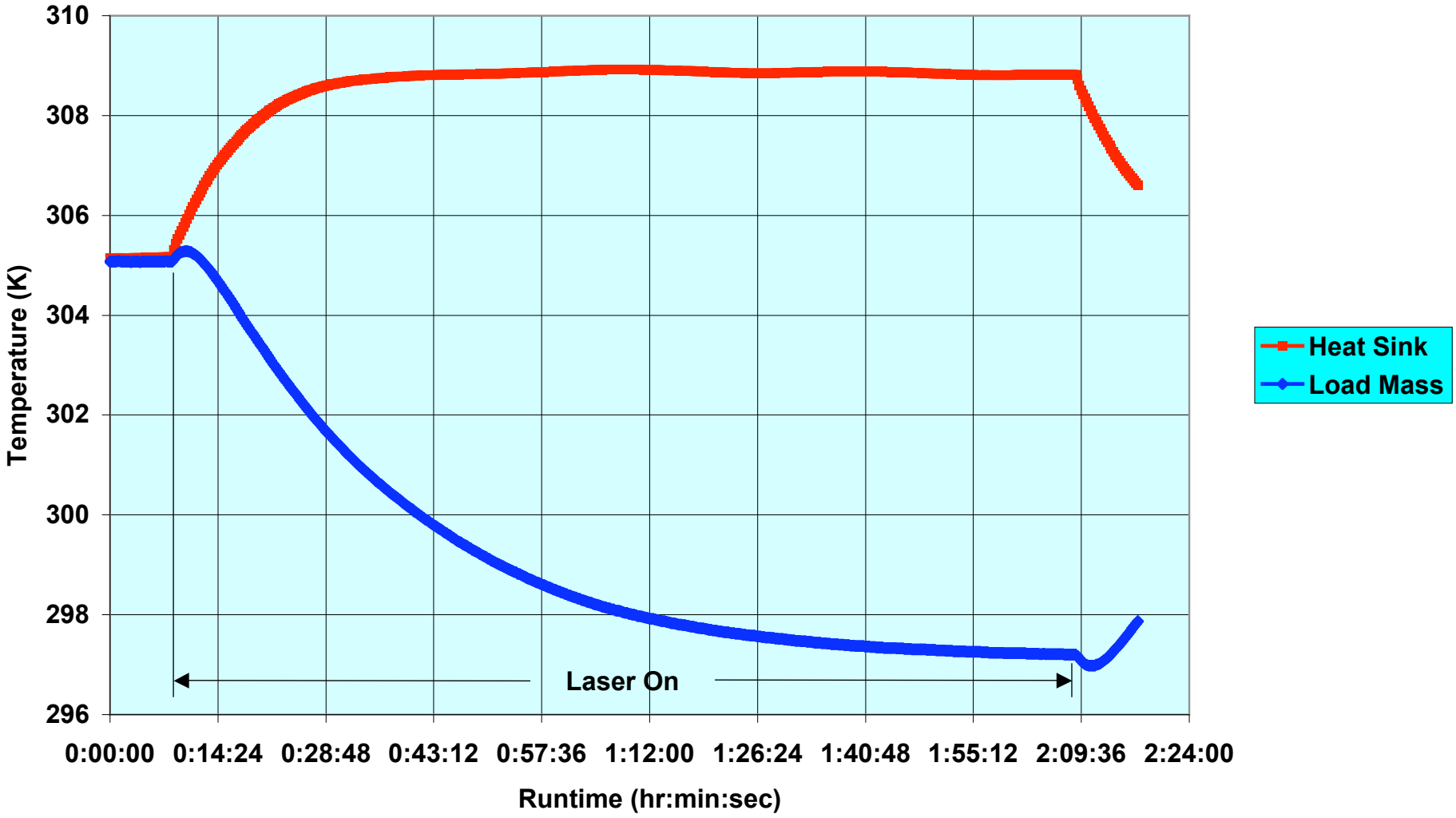
Fluorescent element is Yb doped Zirconium Flouride glass (ZBLAN)

Commercial Yb:YAG Disk Tunable Disk Laser Used to Pump Refrigerator

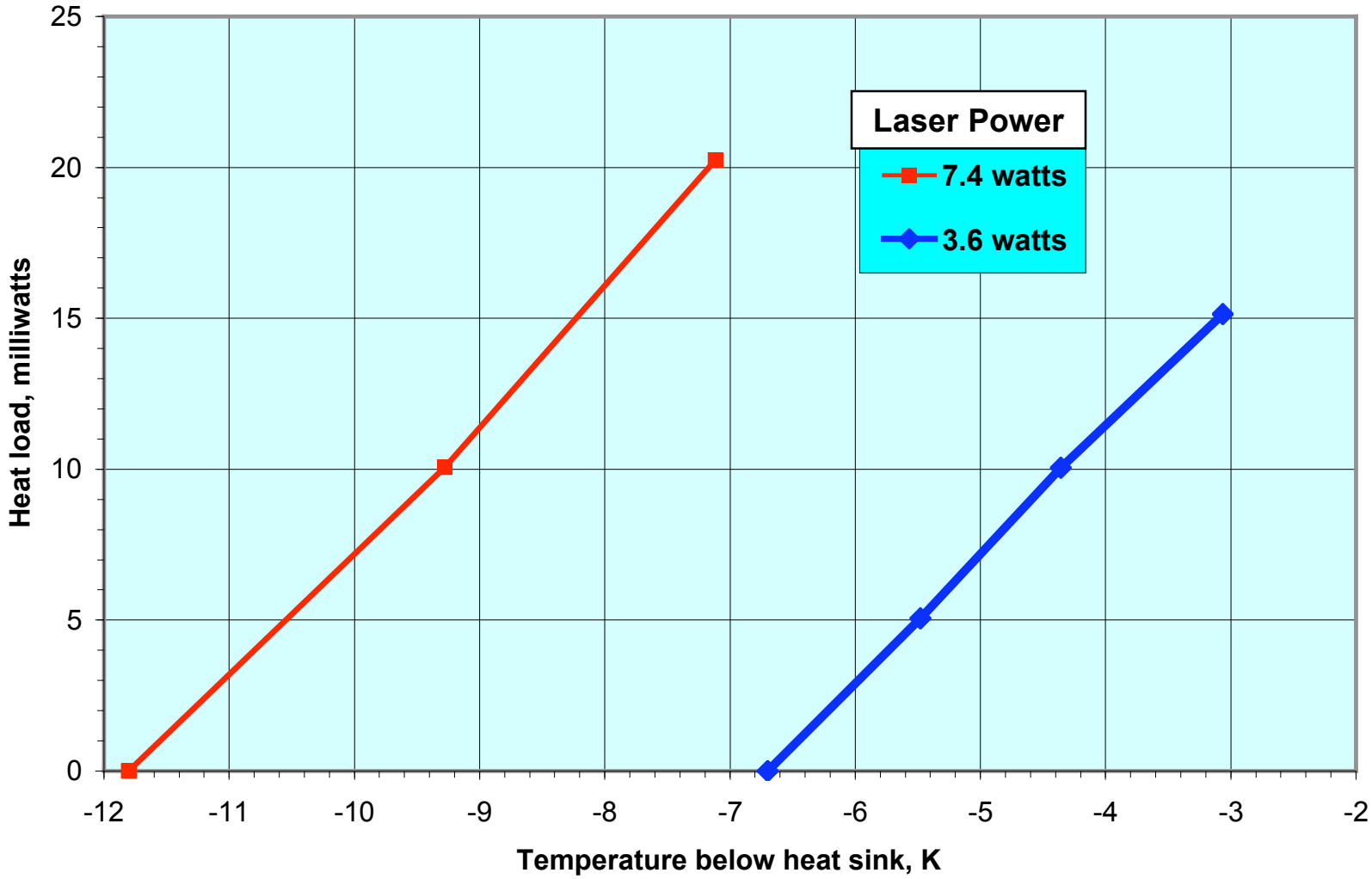


14 watts of laser power results in a steady state temperature 15.6º below heat sink, with 67.4 mK of heat lift

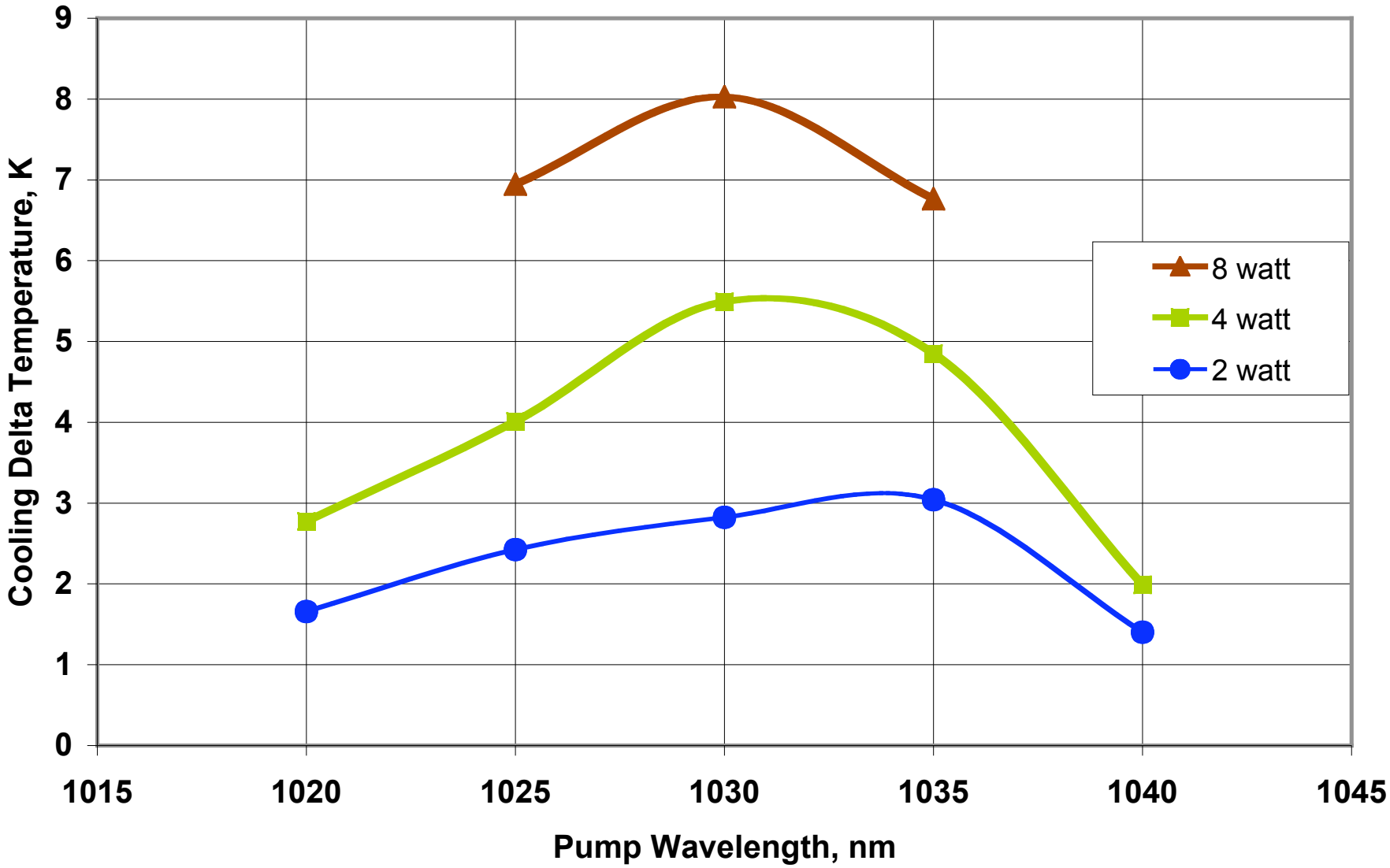
In this typical run, 7.4 watts results in 11.8 °C delta



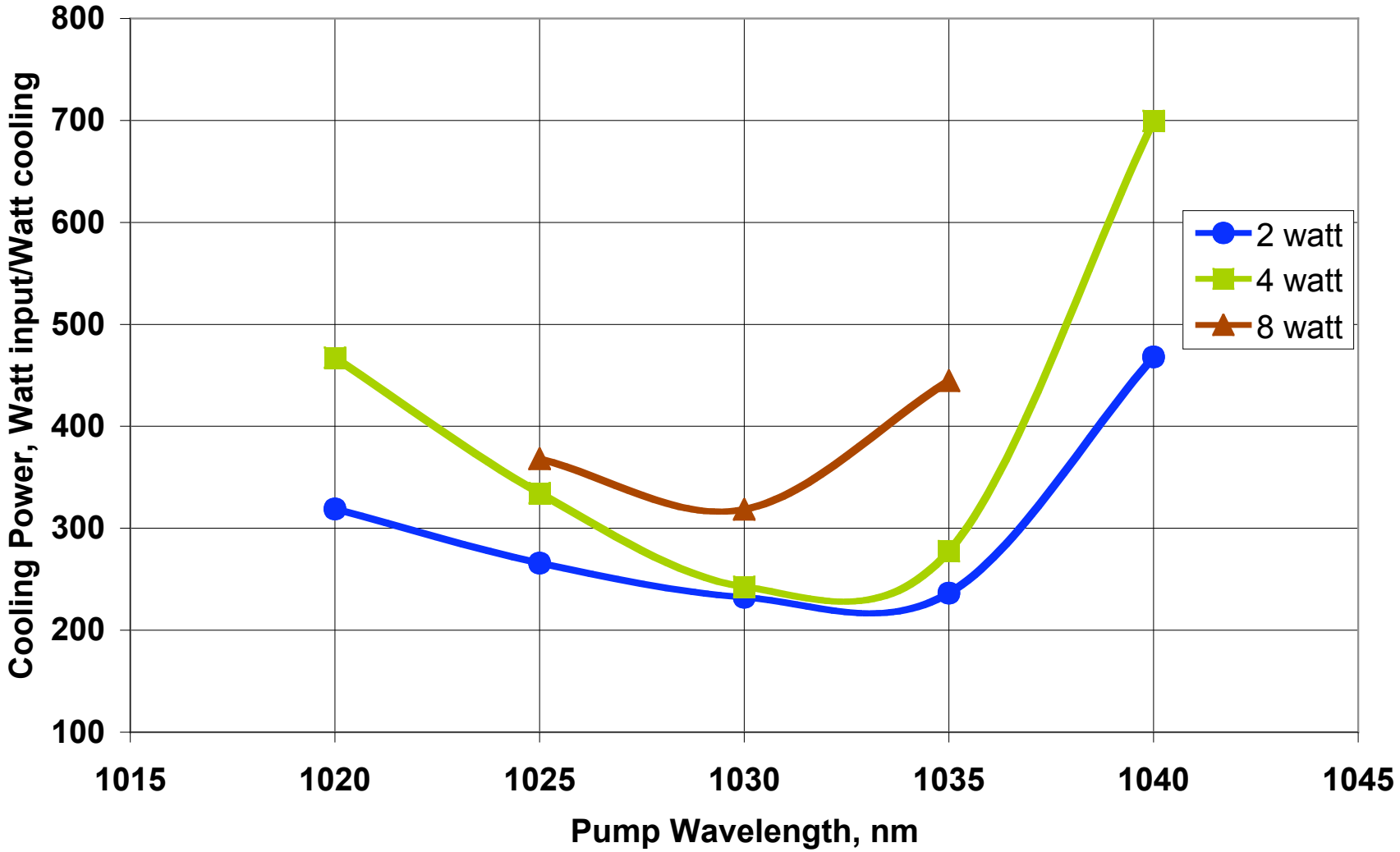
Load Curve Shows Refrigerator Performance Consistent with Measured Conductance



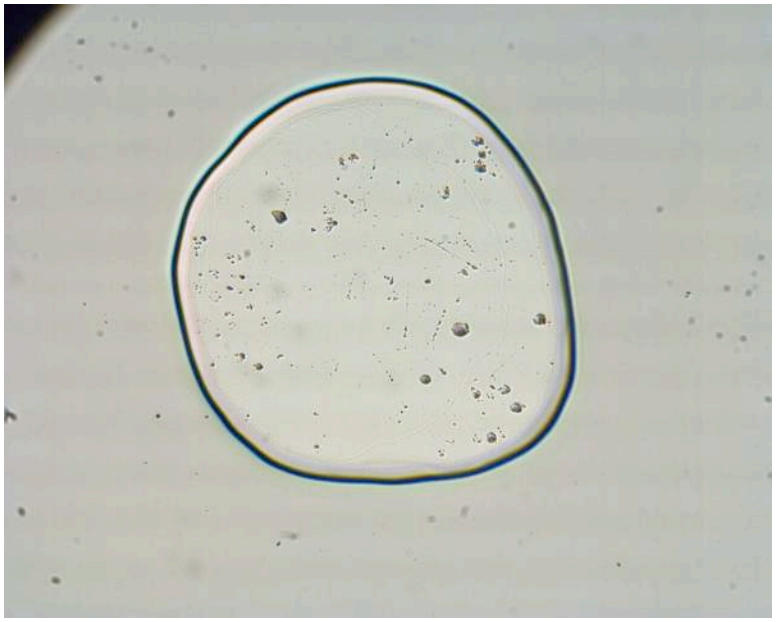
Optimum Pump Wavelength is Near 1030 nm



As Expected, Cooling Efficiency Goes Down as Power is Increased



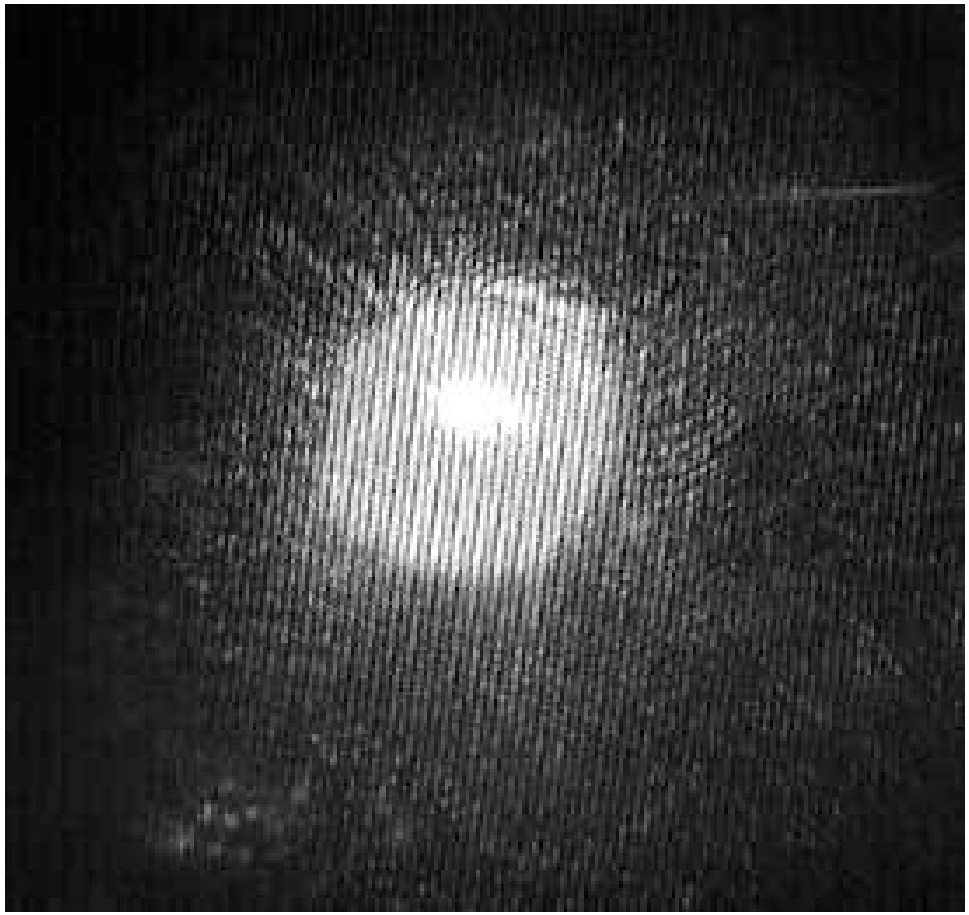
High Intensity Causes Damage at Feedhole



Undamaged Feedhole

Feedhole Damage At Edges after 12 W

Imaging Feedhole and Beam Allows Correct Alignment and De-focus to Prevent Damage



Conclusions

- We have achieved a breakthrough in the proof-of-concept of an optical refrigerator in attaching the fluorescent element to a load
  - Cooled a load 15.6º C below its surroundings
  - Heat lift of 67.4 milliwatts
  - Specific power of 145 watt/watt (laser power/refrigeration)
  - Optimum pump wavelength of 1030 nm
- Several critical issues were overcome
  - Fluorescence leakage through mirrors
  - Beam alignment and focusing
- Follow-On work needs to be done to improve efficiency
  - Current efficiency significantly poorer than predicted
- Application niches emerging
  - Efficiency improvements important
  - Solid state like a TEC but, capable of lower temperatures (80 K)
  - Millimeter scale cooling devices e.g. : 6 mW @ 80 K with 0.5 cm total volume

Trail has been broken to application integration

Technology Readiness Assessment Provides Roadmap for Technology

- TRL 1: *Basic Principles Observed and Reported*
  - LANL in 1995: Less than 1 °C cooling observed in isolated glass
- TRL 2: *Technology Concept Formulated*
  - LANL and Ball 1996 to 1998: Achieve 50 °C cooling in isolated glass
  - Ball in 1999: System design study based on LANL data concludes it is a feasible technology for cooling small devices
- TRL 3: *Technology Critical Function & Proof of Concept* ← *Today*
  - Ball-NASA ATIP program discovered and solved mirror leakage problem; allowing a load to be cooled
  - Load cooled 15.6 °C with 145 watt/watt specific power
- TRL 4: *Concept-Enabling Level of Performance*
  - Will require cooling a load 150 °C (150 K) to be competitive with multi-stage thermoelectrics
  - Will require cooling focal plane 200 °C (100 K) to be really useful for IR and high Tc devices ; will need ~ 35 watt/watt specific power
- TRL 5: *Breadboard in Relevant Environment*
  - Should come quickly after TRL 4 achieved

Acknowledgements

- NASA Earth Science Technology Office who supported the work